Draft version March 15, 2007
Preprint typeset using LaTeX style emulateapj v. 2/19/04

VIRGO GALAXIES WITH LONG ONE-SIDED HI TAILS

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Draft version March 15, 2007

ABSTRACT

In a new HI imaging survey of Virgo galaxies (VIVA: VLA Imaging of Virgo galaxies in Atomic gas), we find 7 spiral galaxies with long HI tails. The morphology varies but all the tails are extended well beyond the optical radii on one side. These galaxies are found in intermediate-low density regions ($0.6-1$ Mpc in projection from M87). The tails are all pointing roughly away from M87, suggesting that these tails may have been created by a global cluster mechanism. While the tidal effects of the cluster potential are too small, a rough estimate suggests that simple ram-pressure stripping indeed could have formed the tails in all but two cases. At least three systems show HI truncation to within the stellar disk, providing evidence for a gas-gas interaction. Although most of these galaxies do not appear disturbed optically, some have close neighbors, suggesting that tidal interactions may have moved gas outwards making it more susceptible to the ICM ram-pressure or viscosity. Indeed, a simulation study of one of the tail galaxies, NGC 4654, suggests that the galaxy is most likely affected by the combined effect of a gravitational interaction and ram-pressure stripping. We conclude that these one-sided HI tail galaxies have recently arrived in the cluster, falling in on highly radial orbits. It appears that galaxies begin to lose their gas already at intermediate distances from the cluster center through ram-pressure or turbulent viscous stripping and tidal interactions with neighbours, or a combination of both.

Subject headings: galaxies: clusters — galaxies: evolution — galaxies: interactions — galaxies: kinematics and dynamics

1. INTRODUCTION

The density-morphology relation (Dressler 1980), indicating an increasing elliptical and S0 population fraction with increasing density, has been known to exist over six orders of magnitude in galaxy density (Postman & Geller 1984). It is only recently that large surveys have shown just how smoothly the galaxy properties change with galaxy density. For example Solanes et al. (2001) find that gas deficiency gradually decreases out to two Abell radii from the cluster center and Lewis et al. (2002) and Gomez et al. (2003) find that the star formation rate depends on local galaxy density. These results have led to the concept that galaxies may already be affected by their environment well before they fall into the dense cluster core (*pre-processing*).

While many processes have been suggested to affect galaxies in the cluster environment such as ram-pressure stripping (Gunn & Gott 1972), starvation (Larson et al. 1980), harassment (Moore et al. 1996) and tidal distortions due to the cluster potential and galaxy-galaxy interactions (Bekki 1999; Mihos 2004), it is still an open question what would affect the galaxies in the lower density outskirts of the clusters. Recently Kenney, van Gorkom & Vollmer (2004) studied one such case, NGC 4522, which is at a large projected distance from the center of Virgo, yet appears to be undergoing ram-pressure stripping due to bulk motions of the ICM, as the M49 subcluster is merging with Virgo proper.

In our new VLA HI survey of the Virgo cluster, we find candidates that appear to be feeling the cluster influence for the first time in the outskirts of the cluster. A number of galaxies located at intermediate distances from M87 reveal long gas tails, all pointing roughly away from the cluster center. Here we test our assumption that these tail galaxies are recent arrivals in the cluster and review possible causes of their gas tails, i.e. how galaxies can be modified before they enter the dense cluster core.

2. VIVA, A NEW VLA HI SURVEY OF VIRGO SPIRALS

VIVA, VLA[5]Imaging of Virgo galaxies in Atomic gas, is a new VLA HI survey of spiral galaxies in the Virgo cluster. The goal of the survey is to study details of different environmental effects. The Virgo cluster is ideal for this study not only due to its nearness but also because it is dynamically young (Binggeli 1999) and very likely to contain various mechanisms at work. We have sampled $\sim$50 galaxies throughout the cluster from near the dense core to the outskirts. The selected galaxies are located at projected distances of 0.3-3.3 Mpc from the cluster center assuming a distance of 16 Mpc to Virgo (Yasuda et al. 1997), which corresponds to $\approx$ 0.4-4.3 virial radii (Tully & Shaya 1984).

The new survey was done with the VLA in the C-short array and additional 10 fields (13 galaxies) previously observed in C array were also included in the database. The typical spatial and spectral resolutions are $15''$ and

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[5] The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation (NSF), operated under cooperative agreement by Associated Universities, Inc.

10 km s^{-1}, respectively, which are a factor of 3 and 4 better than the previous VLA HI survey of Virgo spirals (Cayatte et al. 1990). The rms of the data is typically 0.4 mJy, yielding an HI column density sensitivity of $\approx 6 \times 10^{19}$ cm^{-2} in 3σ.

The data have been calibrated and continuum subtracted with the Astronomical Imaging Processing System (AIPS). The data from the NRAO archive have been processed in the same way as the new survey data. To maximize the sensitivity, we applied a weighting scheme intermediate between uniform and natural but somewhat closer to a natural weighting scheme (robust=1, Briggs 1995). We also made tapered images with twice the beamsize to bring out faint extended features. We will present further details of the observations and the data reduction in Chung et al. (2007, in preparation).

3. HI TAIL GALAXIES IN THE VIRGO CLUSTER

3.1. *Overview of the HI Properties of the Tails*

The survey collected HI data on 53 galaxies in total, 48 spirals and 5 systems of other types (Im, dE). Among them, 7 spiral galaxies revealed a long HI extension (see Plate 1). These tail galaxies have the following properties in common in the HI morphology: 1) the HI is extended well beyond the optical disk only on one side; 2) the tails differ from tidal bridges, i.e. there is no optical counterpart at the tip of the tail down to $r \approx 26$ mag arcsec^{-2} in the Sloan Digital Sky Survey (SDSS) images for extended features like the tails; 3) the projected length of the tail is larger than the half of the symmetric part in HI ($l_t > 0.5 D_{\rm HI}$; see Table 1).

Besides the similarities in gas morphology, the tails are also pointing roughly away from M87 as shown with arrows in Plate 1. These HI tail galaxies are located at intermediate distances of $0.6 - 1$ Mpc from M87 in projection. All but NGC 4654 are found to the west of M87, where the X-ray emission appears to be more elongated. They show a wide range of HI gas deficiency (see Haynes & Giovanelli 1984, for the definition), from -0.56 to 0.8. The HI mass in the tail varies from 10 to 40% of the total. The optical and HI properties are summarized in Table 1 and detailed descriptions of individual tails are given in the following section.

3.2. *Comments on Individual HI Tail Galaxies*

NGC 4299/4294: These two galaxies are separated by 5.7′ ($\approx$ 27 kpc) in projection and $\approx$ 120 km s^{-1} in velocity. The tail of NGC 4294 is almost perpendicular to the stellar (and the HI) disk and pointing to the SW. NGC 4299 has one tail pointing to the SW, parallel to NGC 4294's tail and another tail pointing to SE. The second tail of NGC 4299 is much broader and lower in HI surface density than the other one. The combined HI mass of NGC 4299's tails is $\gtrsim 4 \times 10^8\ M_\odot$, $\approx 36\%$ of the total emission. The HI position-velocity diagram (PVD, Figure 1) shows a 2σ connection between the SE end of NGC 4294's disk, where the stellar disk is more extended. We see no optical counterpart along the HI tails or between the two galaxies down to the limit mentioned.

NGC 4302: The HI is mildly truncated within the stellar disk in the south ($R_{\rm HI}/R_{25} \approx 1$, but a faint stellar envelope is seen beyond the HI disk) and the gas tail is extended to the north with no optical counterpart. A

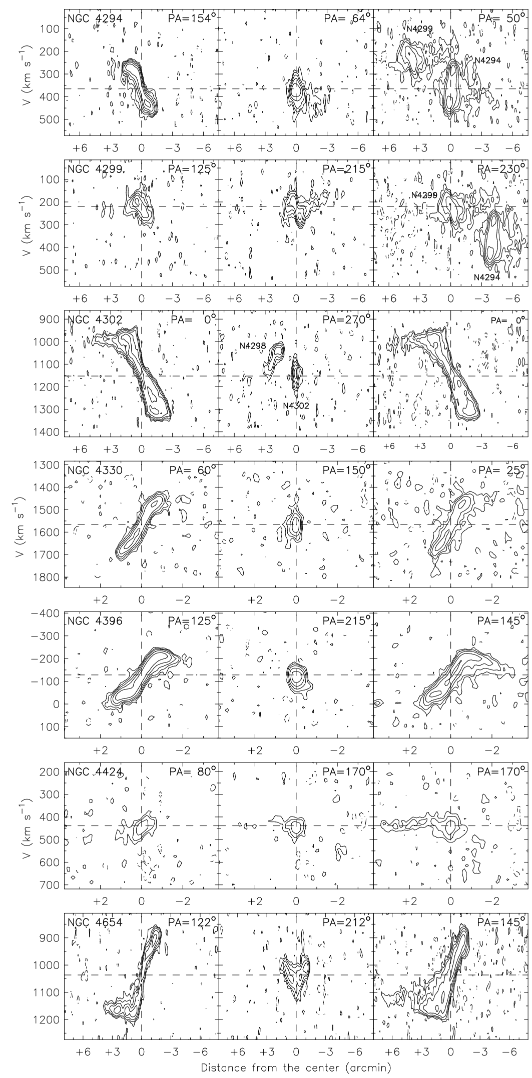

FIG. 1.— For each galaxy, the first two figures from the left are the PVDs on the disk along the major (left) and the minor (middle) axis. The figure on the right shows the PVD summed over the tail to the perpendicular direction of the tail. The angle of the cut is indicated in top-right corner. The dashed line represents the center in the position and the velocity. From top to bottom, the widths of the cuts are 4.0′, 3.3′, 2.2′, 2.5′, 2.3′, 2.7′, and 3.9′, the contours for the PVDs along the major/minor axis are -4, -2, 2, 4, 8, 16, 32..., ×0.25, 0.25, 0.26, 0.26, 0.24, 0.29, 0.38 mJy beam^{-1}, and for the PVDs along the tails, (same)×4.0, 3.0, 2.5, 2.5, 3.0, 4.0 mJy beam^{-1}.

nearby galaxy, NGC 4298 is only 2.4′ ($\approx$ 11 kpc) to the west at a similar velocity ($\Delta v \approx 30$ km s^{-1}). The HI of NGC 4298 is more extended to the NW while its stellar disk is more extended to the SE. The two galaxies overlap in velocity but there is no HI in between down to 2σ. While NGC 4298 looks disturbed both optically and in HI, NGC 4302 does not show any obvious signatures of a tidal disturbance.

NGC 4330: Its HI gas is truncated within the stellar disk to the NE ($R_{\rm HI}/R_{25} \approx 0.75$) and the HI tail extends to the SW. A deeper optical image shows that also to the SW the undisturbed stellar disk extends well beyond the HI tail (Abramson et al., in preparation). We do not see any obvious optical counterpart along the HI tail but

TABLE 1
Properties of the Virgo Hi Tail Galaxies

	– General properties –				———— Hi properties ————								– Global parameters[b] –			—— Neighbor ——			
NGC	Type	B_T mag	V_{rad} km/s	D_{25} kpc	$D_{\rm HI}$ kpc	$M_{\rm HI}$ $10^8 M_\odot$	V_{rot}[a] km/s	$def_{\rm HI}$	l_{tail} kpc	w_{tail} kpc	M_{tail} $10^8 M_\odot$	Σ_{tail} 10^{19}/cm^2	d_{87} Mpc	$\rho_{\rm ICM}$ 10^{-4}/cm^3	$M(d_{87})$ $10^{14} M_\odot$		Δv km/s	Δd kpc	ΔB_T mag
4294	SBc	12.3	359	14	17	15.9	172	−0.17	27	8.2	2.0	11-26	0.7	1.04	0.97	N4299	127	27	0.2
4299	SABd	12.5	237	7	12	11.8	169	−0.56	14	9.0	2.6	11-18	0.7	1.09	0.93	N4294	127	27	0.2
4302	Sc	12.5	1150	24	26	14.9	199	0.39	16	8.9	0.9	10-20	0.9	0.74	1.24	N4298	14	11	0.5
4330	Sc	13.1	1564	25	13	4.1	180	0.80	13	5.0	0.4	6-13	0.6	1.19	0.86	V0706	75	77	4.3
4396	Scd	13.1	-125	15	14	9.9	170	0.28	13	3.6	0.7	19-39	1.0	0.64	1.37	N4419	133	186	1.1
4424	SBa	12.4	439	16	10	1.7	158	0.75	22	10.7	0.8	3-6	0.9	0.77	1.21	N4445	79	74	1.2
4654	Sc(R)	11.0	1038	23	28	34.3	300	0.06	32	12.9	4.1	20-47	0.9	0.68	1.32	N4639	27	81	1.2

[a]It was determined from Hi position-velocity cut along the major axis except for NGC 4424, which was estimated from H-band mag.
[b]$\rho_{\rm ICM}$ and $M(d_{87})$ have been estimated assuming the β-model (Schindler, Binggeli & Böhringer 1999) with the same coefficients for the Virgo cluster presented as in Vollmer et al. (2001).

its GALEX (Galaxy Evolution Explorer) image shows a UV tail from the SW end of the optical disk along the Hi to the NW, which is displaced from the optical disk.

NGC 4396: The Hi morphology resembles that of NGC 4330, except that at the opposite side of the Hi tail (the SE) the Hi extends as far as the stellar disk. At that side the Hi is compressed and Hα emission from star formation is enhanced. Along the tail no stellar light or UV is seen down to the SDSS and GALEX limits.

NGC 4424: The Hi is severely truncated within the optical disk ($D_{\rm HI}/D_{25} \approx 0.5$) and the tail extends from the south to SW. The tail shows a weak velocity gradient (Fig. 1) toward M49 as well as M87. The tail is clearly detected out to $\sim 10'$ (47 kpc), although there is a hint of faint gas even further to the SW in the direction of M49, which itself is the center of a subcluster of galaxies (Plate 1). The stellar morphology and kinematics appear to be strongly disturbed by a gravitational interaction (Kenney et al. 1996; Cortés et al. 2006).

NGC 4654: This is the only galaxy in the tail sample that also has a strong asymmetry in the stellar disk. The Hi shows a compressed edge on one side and a long tenuous tail on the other side. SDSS images show that starlight extends beyond the ridge of compressed Hi in the west, implicating an ICM-ISM interaction as Phookum & Mundy (1995) suggested.

4. DISCUSSION

The tail galaxies are located at intermediate distances from the cluster center at a projected distance of 0.6-1 Mpc from M87. The length and the width of the tails vary, but the tails are all pointing roughly away from the cluster center (M87), suggesting that a single global mechanism such as the cluster potential or ram-pressure due to the ICM might be responsible for these Hi tails.

The cluster potential however, is not enough to affect galaxies significantly at those distances. The tidal acceleration due to the cluster potential ($\approx 2GMR/d^3$, $d \gg R$ where G is the gravitional constant, M is the cluster mass within a radius d, and R is the size of the galaxy) is typically $\sim$2 (km s^{-1})^2 kpc^{-1} while the gravitational acceleration of the galaxy (V_{rot}^2/R where V_{rot} is the galaxy's rotational velocity) is always larger than the cluster potential by 3 orders of magnitude, with a typical value of 5×10^3 (km s^{-1})^2 kpc^{-1}.

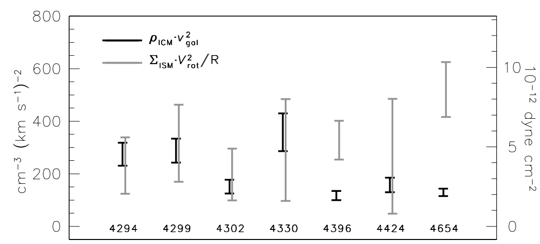

Fig. 2.— The range of ram-pressure due to the ICM and the restoring force per unit area on the disk for tail galaxies are presented with a bar.

Alternatively galaxies can be gas stripped by ram-pressure when $\rho_{\rm ICM} \cdot v_{gal}^2 > \Sigma_{\rm ISM} \cdot V_{rot}^2/R$, where $\rho_{\rm ICM}$ is the ICM density, v_{gal} is the galaxy's velocity $w.r.t.$ the ICM, and $\Sigma_{\rm ISM}$ is the ISM surface density (Gunn & Gott 1972, see also Voller 2001). In Figure 2 we compare the estimated ram-pressure strength with the restoring force per unit area in the disk of each galaxy. Rather than using the observed radial velocities, we use the simulations of Vollmer et al. (2001) to estimate the range of relative velocities a galaxy can have at a given projected distance from the cluster center (1250 to 1900 km s^{-1}). The error bar in the ram-pressure indicates this range. The main uncertainty in the restoring force is the surface density of the gas at the time of stripping. We considered two extremes, the mean Hi surface density in the tail, and the peak value measured in the tail. Figure 2 shows that ram-pressure could exceed the restoring force for 5 out of 7 galaxies.

As seen in Plate 1, NGC 4330, NGC 4424 and NGC 4302 (and its neigbour NGC 4298) clearly show that their Hi disk is truncated to well within the stellar disk indicating that these three galaxies must have been affected by a gas-gas interaction. The systemic velocity of NGC 4330 and NGC 4302 is close to the cluster mean, indicating that they move mostly in the plane of the sky. This combined with the fact that their Hi tails point away from the cluster center, suggests these galaxies are falling into the cluster along highly radial orbits. NGC 4424, whose systemic velocity is highly blueshifted with respect to the cluster mean, could be falling in from the back. Another possibility is that it has passed close to M49 and has been stripped by the ICM of that subcluster. Its tail points directly toward the subcluster. In this scenario the NGC 4424 tail would be more comparable to another tail in Virgo recently found by Oosterloo & van Gorkom (2005), which appears to be gas stripped from NGC 4388 by the hot ICM gas in the subgroup of M86. Similarly a passage close to M49 could have caused the gravitational disturbance of NGC 4424, as M86 might have gravitationally disturbed NGC 4388.

At the other extreme, the two galaxies for which our simple estimate of ram-pressure appears too low to have an effect, still show signs of gas-gas interaction. Both galaxies, NGC 4396 and NGC 4654, have HI compressed on one side, while the HI tail at the opposite side does not seem to have an optical counterpart. In deeper optical images, NGC 4654 reveals more stellar light beyond the HI disk to the NW (§ 3.2). In fact Vollmer (2003) concludes that the HI morphology and kinematics of NGC 4654 can best be explained by the combined effect of ram-pressure stripping and a tidal disturbance by its companion, NGC 4639. On the other hand, NGC 4396 looks optically undisturbed. Several explanations are possible, either the galaxy is affected by viscous turbulent stripping instead of the simple momentum transfer, or the ICM pressure is enhanced due to bulk motions or local clumping of the gas, as it is likely in NGC 4522 (Kenney et al. 2004).

Additionally, the kinematics of the tails also support an ICM-ISM interaction for most cases. For all galaxies except NGC 4294 and possibly NGC 4330, the velocity gradient in the HI tails is toward the cluster mean (Fig. 1) as it is expected if the HI gas has been stripped by the cluster gas.

We have seen for NGC 4654 that the tidal interaction with a nearby companion could have made the galaxy more vulnerable to ram-pressure stripping. We may well ask whether tidal interactions with neighbors could help explain the existence of the other tails. Mihos (2001, 2004) shows that if galaxies fall in as groups, the effect of the cluster potential gets greatly enhanced. In Table 1 we list the nearest companion for each of the galaxies. Almost all have neighbors that are close in projection (<100 kpc) and in velocity (<100 km s^{-1}). In a dense cluster environment being close in projection does not necessarily imply physical association, on the other hand the cumulative effect of many distant encounters can also loosen the outer parts (harassment). It is thus not unlikely that gravity plays some role, yet morphologically all the systems show some evidence for gas-gas interactions as well. The only exception is the NGC 4299/4294 pair, although a parallel orientation of two tidal tails is rarely seen in interacting systems, and the tails have no stellar counterparts down to the SDSS limit. In analogy with the Mihos (2004) result tidal interactions may make it more easy to ram-pressure strip galaxies by bringing material to the outer disk (Vollmer & Huchtmeier 2006).

To conclude, while previous HI imaging showed that highly HI deficient galaxies in the center of Virgo have very small HI disks (e.g. Cayatte et al. 1990), we are now providing HI images of galaxies that are beyond the strongly HI deficient zone (> 0.5 Mpc; Cayatte et al. 1990, see also Fig. 3 in Solanes et al. 2001). Our images show how galaxies just outside the virial radius may begin to lose their gas. In this region (0.6−1 Mpc from M87), seven of the 16 galaxies imaged by us (out of 27 spiral galaxies in the VCC catalog with m_p <13.75, Binggeli, Sandage & Tammann 1985) show HI tails. Thus at least 26% of the large spiral galaxies in this region of Virgo seem to be recent arrivals being stripped of gas. Interestingly, since it only affects the loosely bound gas in the outer parts of the galaxies, the simple momentum transfer ram-pressure picture still works for most of these galaxies, though viscous turbulent stripping, which can remove the gas more efficiently from edge-on encounters *w.r.t.* the ICM (Nulsen 1982), could affect some galaxies (e.g. NGC 4302). It seems then that galaxy preprocessing occurs through mild gas-gas and/or tidal interactions before the galaxies enter the dense part of the cluster. Once they are within a virial radius gas gets removed within a gigayear through momentum transfer ram-pressure stripping of the more higly radially infalling galaxies and possibly viscous turbulent stripping of galaxies on more circular orbits.

This work has been supported in part by NSF grants to Columbia University and Yale University.

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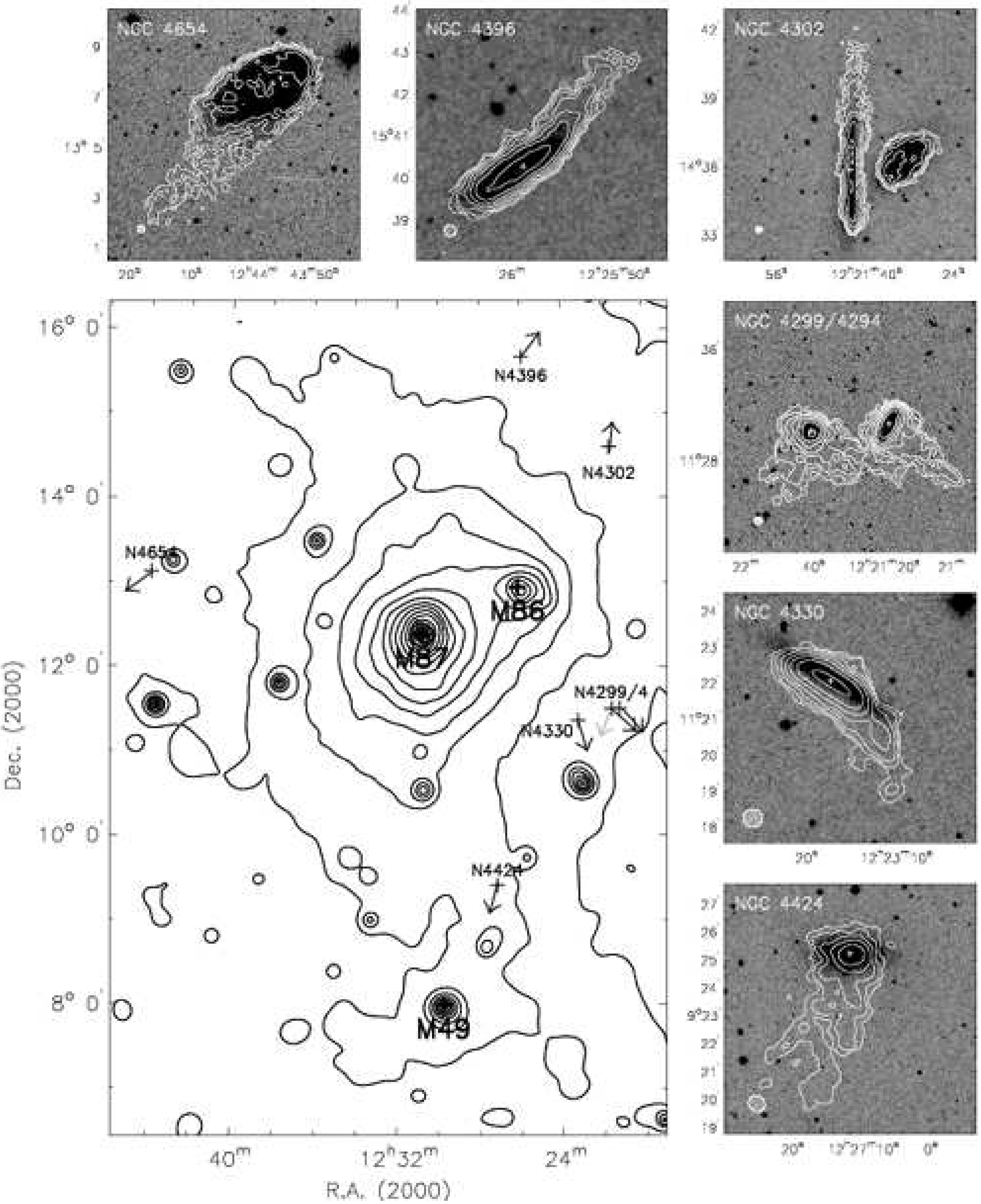
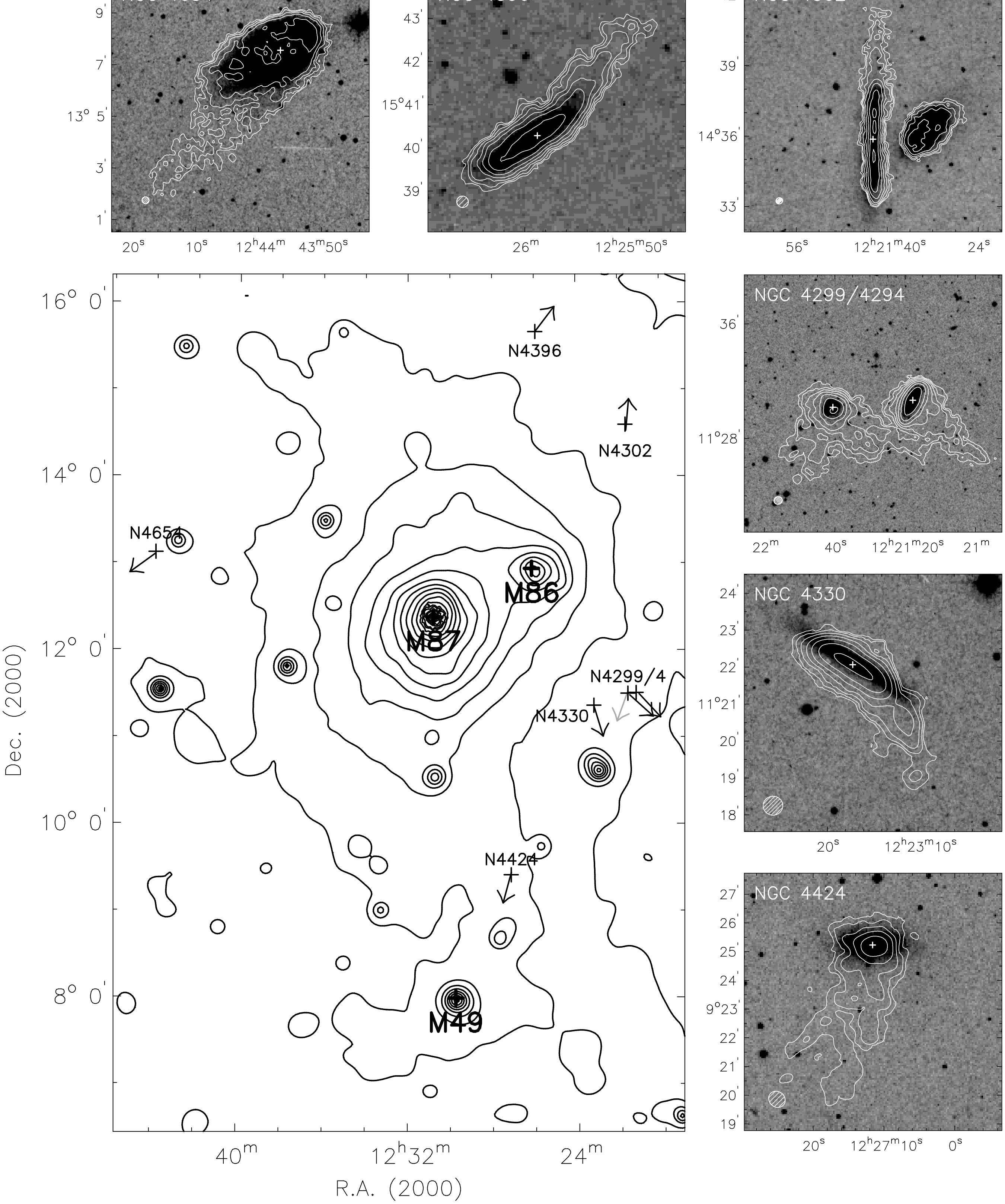


FIG. 3.— (Plate 1) bottom-left) The locations of the HI tail galaxies are shown with the cross on the X-ray background of the Virgo region (0.5−2.0 keV, ROSAT; Böhringer et al. 1994). The directions of the tails are indicated with the arrow. The second tail of NGC 4299 (E tail) is shown in lightgray. Seven figures on the top and on the right, we show zoomed views of individual galaxies. The HI contours (white) are shown overlaid on the Digitized Sky Survey (DSS) image in grayscale. The galaxy name and the synthesized beam size appear in the upper-left and the bottom-left corner in each box. The white crosses indicate the optical center. The HI contours are 2.8 (NGC 4294/9), 6.7 (NGC 4302), 2.2 (NGC 4330), 4.3 (NGC 4396), 1.9 (NGC 4424), 13.0 (NGC4654)×1, 2, 4, 8, 16, ... in 10^{19} cm^{-2}.



NGC 4299/4294
NGC 4330
NGC 4424
N4396
N4302
N4654
M86
M87
M49
N4299/4
N4330
N4424
Dec. (2000)
R.A. (2000)
16° 0'
14° 0'
12° 0'
10° 0'
8° 0'
40m
12h32m
24m